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Fatigue Properties of Nonferrous
Alloys for Heat Exchangers,
Pumps, and Piping

Assignment 86 108
MEL R&D Report 232/66
May 1966

By

M. R. Gross and R. C. Schwab

U. S. NAVY

MARINE ENGINEERING LABORATORY

Annapolis, Md.

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ABSTRACT

The fatigue behavior of 13 nonferrous alloys used for corrosion-resistant heat exchangers, pumps, and piping systems was investigated over a broad life spectrum of 100 to 100-million cycles. Both cast and wrought copper-base and nickel-base alloys were studied. It is concluded that wrought Monel* and forged Ni-Al bronze have the highest fatigue strengths, whereas gun metal and valve bronze have the lowest. The effect of salt water on fatigue performance was not found to be highly significant. The use of Langer's equation to predict stress-cycle relationships gave satisfactory results for wrought alloys but appeared to be overly conservative for cast alloys.

*Registered trade name of the International Nickel Company, Incorporated.

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Introduction

Many copper-base and nickel-base alloys are used in the construction of heat exchangers, pumps, and piping systems designed to handle fresh or saline water. In the selection of materials for such applications, consideration is given primarily to corrosion resistance, erosion resistance, and heat transfer characteristics. In most applications the applied stress levels are low. Accordingly, the structural strength properties of the materials are relatively unimportant.

In recent years, more and more attention has been given to the structural properties of these alloys because of (1) cost and weight reduction programs, (2) conservation of strategic materials, (3) development of new high-strength alloys, and (4) new applications which impose high stress levels. Typical of the latter are sea-connected cooling systems for hydrospace vehicles.

One of the most likely modes of mechanical failure in systems undergoing cyclic pressurization or thermal shock loading is metal fatigue. The frequency of stress cycling in such systems may vary from that of an occasional start-up and shutdown to vibrational forces developed by the movement of the heat-exchanger fluids. Little or no published information on the alloys used in this type of service was found in reviewing the literature several years ago. Accordingly, tests were conducted at the U. S. Navy Marine Engineering Laboratory to establish the fatigue behavior of

ariety of corrosion-resistant nonferrous alloys. The results these tests are presented in this paper.

erials Investigated

The 13 alloys investigated are listed in Table 1, together h their chemical compositions and tensile properties. luded are the strength coefficient, K, and strain-hardening onent, n, contained in the true-stress/true-strain relation- p:

$$\sigma = K \epsilon^n$$

ere are some deficiencies in the tensile properties of the cast terials with respect to the governing specifications. This is be expected inasmuch as the specification requirements are ally based on separately cast test coupons, whereas the values ven in Table 1 were obtained on specimens removed from cast ates.

thod of Test

Two types of flexural fatigue specimens were used in the vestigation. The high-cycle fatigue tests were performed with tating cantilever-beam specimens having the dimensions shown in gure 1. These were constant deadweight load tests with a cycle equency of 1450 cpm. The smooth test lengths were circum- rentially and longitudinally polished to a metallographic nish.

Table 1
Chemical Composition and Mechanical Properties of Alloys

Alloy	Type	Condition	Specification	Chemical Composition - % Cu	Ni	Fe	Mn	Zn	Al	Sn	Si	Others	Mechanical Properties YS (0.2% Offset) ksi	TS ksi	Elong % in 2 in.	RA %	K ksi	n	Hardness Rb	E x 10^6 psi
Gun Metal (Comp G)	C	As-cast	MIL-M-16576	87.2	0.7	0.02	-	3.5	-	8.4	-	-	15.6	38.7	44	39	83	0.45	40	15
Valve Bronze (Comp M)	C	As-cast	MIL-B-16541	88.5	0.5	0.01	-	3.8	-	5.6	-	Pb-1.6 P-0.01	15.8	28.0	17	20	58	0.34	39	14
Ni-Al Bronze	C	As-cast	MIL-B-21230 Alloy 1	80.1	5.2	3.7	0.7	-	10.3	-	-	-	42.1	97.3	14	16	181	0.32	90	13
Ni-Al Bronze	F	Annealed	QQ-B-679 Comp 2	81.2	4.5	2.8	0.9	-	10.6	Nil	-	-	51.8	103.3	16	15	206	0.28	99	17
Superston 40	C	As-cast	MIL-B-21230 Alloy 2	74.6	2.2	3.3	12.5	-	7.4	-	-	-	43.4	85.4	20	24	154	0.26	82	18
70-30 Cupronickel	C	As-cast	MIL-C-20159	66.8	30.4	0.5	1.25	-	-	-	0.5	Cb 0.5	48.1	79.2	23	39	151	0.27	73	18
70-30 Cupronickel	W	Annealed	MIL-C-15726	68.6	29.6	0.6	0.9	0.2	-	-	-	-	20.2	58.5	49	70	116	0.21	58	22
90-10 Cupronickel	W	Hard	MIL-C-15726	88.0	10.0	1.3	0.6	0.04	-	-	-	Pb <0.02	49.6	53.8	33	77	73	0.09	69	20
Cufenloy-40	W	Annealed	-	55.0	Rem	2.2	1.4	0.06	0.01	0.01	-	Pb-0.01 As-0.01	22.4	70.3	50	78	174	0.48	59	24
Cufenloy-40	W	DSR*	-	55.0	Rem	2.2	1.4	0.06	0.01	0.01	-	Pb-0.01 As-0.01	68.4	79.0	26	72	110	0.10	90	20
Cupronickel - 707	W	Annealed	-	64.1	29.6	5.4	0.8	0.11	-	<0.05	0.02	C-0.03 Pb-0.01	51.0	81.6	33	48	148	0.25	83	22
Monel "E"	C	As-cast	QQ-N-288 Class "E"	30.3	63.1	2.2	0.9	-	-	-	1.6	C-0.1 Cb-1.6	27.0	59.5	23	24	128	0.36	70	23
Monel	W	Annealed	MIL-N-894 Class A	32.7	65.0	0.9	1.0	-	0.02	-	-	-	33.1	83.6	46	70	167	0.35	76	26

*Drawn and Stress relieved.
C - Cast; F - Forged; W - Wrought
YS - Yield Strength
TS - Tensile Strength
Elong - Elongation
RA - Reduction of Area

The low-cycle fatigue tests were performed with equipment ibed previously.[1] Flat flexure-type specimens having the sions shown in Figure 2 were used. The short end of the men was held stationary, while the long end was flexed en mechanical stops by a hydraulic piston. One or more n gages (0.25-inch gage length) were attached to the mini- est section to record the longitudinal strain. The applied ng force was measured with a load cell. The total strain , $\Delta\epsilon_T$, was obtained from strain gage readings, and the al bending-stress range was calculated from elastic stress las using the measured load range. Specimens were cycled cpm.

All of the fatigue tests were of the completely reversed (Fatigue ratio = -1). Whereas most of the specimens were d in air, a few were tested with Severn River water con- usly wetting the test surface. Severn River water is a ish estuary water containing 1/6 to 1/3 the salt content tural seawater, depending on the season and the tide. ous fatigue tests in both Severn River water and natural ter have shown no significant differences in the effects e two media.

re Criteria

Failure in the high-cycle, rotating cantilever-beam tests sted of complete fracture. Failure in the low-cycle fatigue

tests was defined as one or more surface cracks 3/16 to 1/4 inch in length.

Results of Tests

The results of the tests are plotted in log-log form in Figures 3 through 15. Two methods have been used in analyzing the data. The top graph in each figure is the S_R vs N relationship for the data, where S_R is the nominal reversed bending stress and N is the number of cycles to failure. S_R was calculated from the elastic stress formula

$$S_R = \frac{\Delta Mc}{2I} \qquad \ldots\ldots (1)$$

where ΔM = bending moment range, in-lb.

c = distance from neutral axis to outermost fiber at minimum cross section, in.

I = moment of inertia of minimum cross section, $in.^4$

The bottom graph in each figure is the S_{PE} vs N relationship for the data, where S_{PE} is the reversed pseudoelastic or apparent elastic stress calculated as follows:

$$S_{PE} = \frac{\Delta \epsilon_T \cdot E}{2} \qquad \ldots\ldots (2)$$

where $\Delta \epsilon_T$ = total strain range as determined from strain gages on the test section, in/in.

E = modulus of elasticity (Table 1), psi.

urvilinear relationship between S_{PE} and N was obtained bv fitting the following relationship to the data.

$$S_{PE} = \frac{C}{N^m} + S_E \qquad \ldots\ldots (3)$$

C and m = best-fit constants

S_E = endurance limit or fatigue strength at 10^8 cycles, psi.

est-fit equation for the S_{PE} vs N data is given in each e.

Equation (3) is a generalization of the following equation sed by Langer[2] for predicting the S_{PE} vs N fatigue curve tensile test data.

$$S_{PE} = \frac{E}{4N^{0.5}} \ln\left(\frac{100}{100-RA}\right) + S_E \qquad \ldots\ldots (4)$$

RA = reduction of area, percent.

The dashed line in each figure is Langer's predicted curve on Equation (4) and the tensile data presented in Table 1. The triangle symbols in graphs represent specimens which been continuously exposed to salt water during the fatigue

rison of Fatigue Strengths

Table 2 represents an attempt to rationalize the fatigue for the 13 alloys investigated. The S_R and S_{PE} values were from the curves in Figures 3 through 15. The values in column were then ranked in order of decreasing fatigue

strength. An average rank for each material is shown in the right hand column.

Table 2

Comparison of Fatigue Strengths of Alloys Investigated

Alloy	Type	Condition	Fatigue Strength At. 10^3 Cycles S_R ksi	10^3 Cycles S_{PE} ksi	10^5 Cycles S_R ksi	10^5 Cycles S_{PE} ksi	10^8 Cycles S_R ksi	10^8 Cycles S_{PE} ksi	Average Rank
Gun Metal	Cast	As-cast	35(12)	96(12)	17(12)	25(12)	6(12.5)	8(12.5)	(12.2)
Valve Bronze	Cast	As-cast	32(13)	52(13)	16(13)	17(13)	6(12.5)	8(12.5)	(12.8)
Ni-Al Bronze	Cast	As-cast	78(6)	210(5)	46(4)	48(7)	29(3)	30(3)	(4.7)
Ni-Al Bronze	Forged	Annealed	110(1)	230(3)	65(1)	64(1)	35(1.5)	37(1)	(1.4)
Superston 40	Cast	As-cast	83(4)	230(3)	44(5)	50(5)	25(5.5)	25(5.5)	(4.7)
70-30 Cupronickel	Cast	As-cast	70(8)	130(11)	32(10)	27(11)	13(11)	14(11)	(10.3)
70-30 Cupronickel	Wrought	Annealed	57(11)	180(7)	29(11)	54(2)	25(5.5)	25(5.5)	(7.0)
90-10 Cupronickel	Wrought	Hard	74(7)	160(8.5)	38(7)	40(8)	21(8)	21(9)	(7.9)
Cufenloy 40	Wrought	Annealed	58(10)	230(3)	35(8)	38(9)	26(4)	26(4)	(6.3)
Cufenloy 40	Wrought	DSR	100(2)	160(8.5)	48(3)	50(5)	20(9)	23(7.5)	(5.8)
Cupronickel-707	Wrought	Annealed	90(3)	190(6)	50(2)	50(5)	22(7)	23(7.5)	(5.1)
Monel "E"	Cast	As-cast	62(9)	155(10)	34(9)	36(10)	16(10)	16(10)	(9.7)
Monel	Wrought	Annealed	80(5)	350(1)	40(6)	52(3)	35(1.5)	33(2)	(3.1)

Note: Numeral in ( ) is rank of value.

Conclusions

From the data and curves presented in Figures 3 through 15, the following conclusions have been reached relative to the unnotched fatigue behavior of the materials investigated.

- Variations in fatigue strength or life are greater for cast alloys than for wrought alloys.

- The fatigue strength of a wrought alloy is superior to :t of a cast alloy of comparable chemical composition.

- Wrought Monel and forged Ni-Al bronze have the highest .igue strengths, whereas gun metal and valve bronze have the 'est.

- Stress-cycle relationships predicted by Langer's equation generally satisfactory for wrought alloys but appear to be rly conservative for most cast alloys.

- Salt water does not have a highly significant effect on fatigue behavior of the alloys investigated.

erences

Gross, M. R., "Low-Cycle Fatigue of Materials for Submarine Construction," Naval Engineers Jour, Vol. 75, No. 5, Oct 1963, pp. 783-797

Langer, B. F., "Design of Pressure Vessels for Low-Cycle Fatigue," Jour of Basic Engineering, ASME Trans. Ser. D, Vol. 84, Series D, No. 3, Sep 1962, pp. 389-402

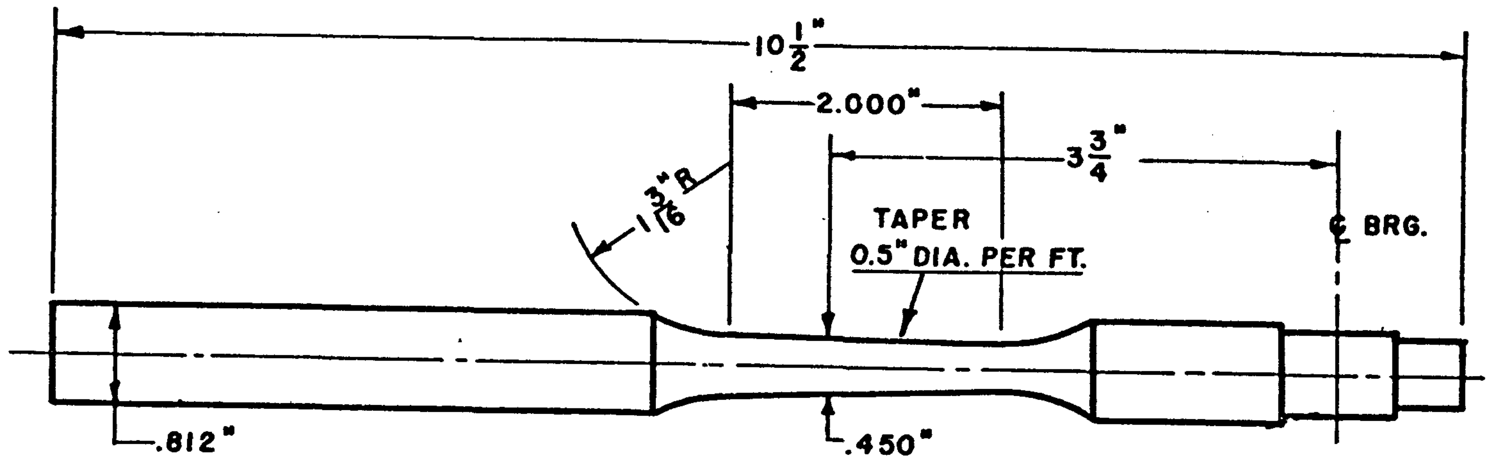

Figure 1

Rotating Cantilever Beam Fatigue Specimen

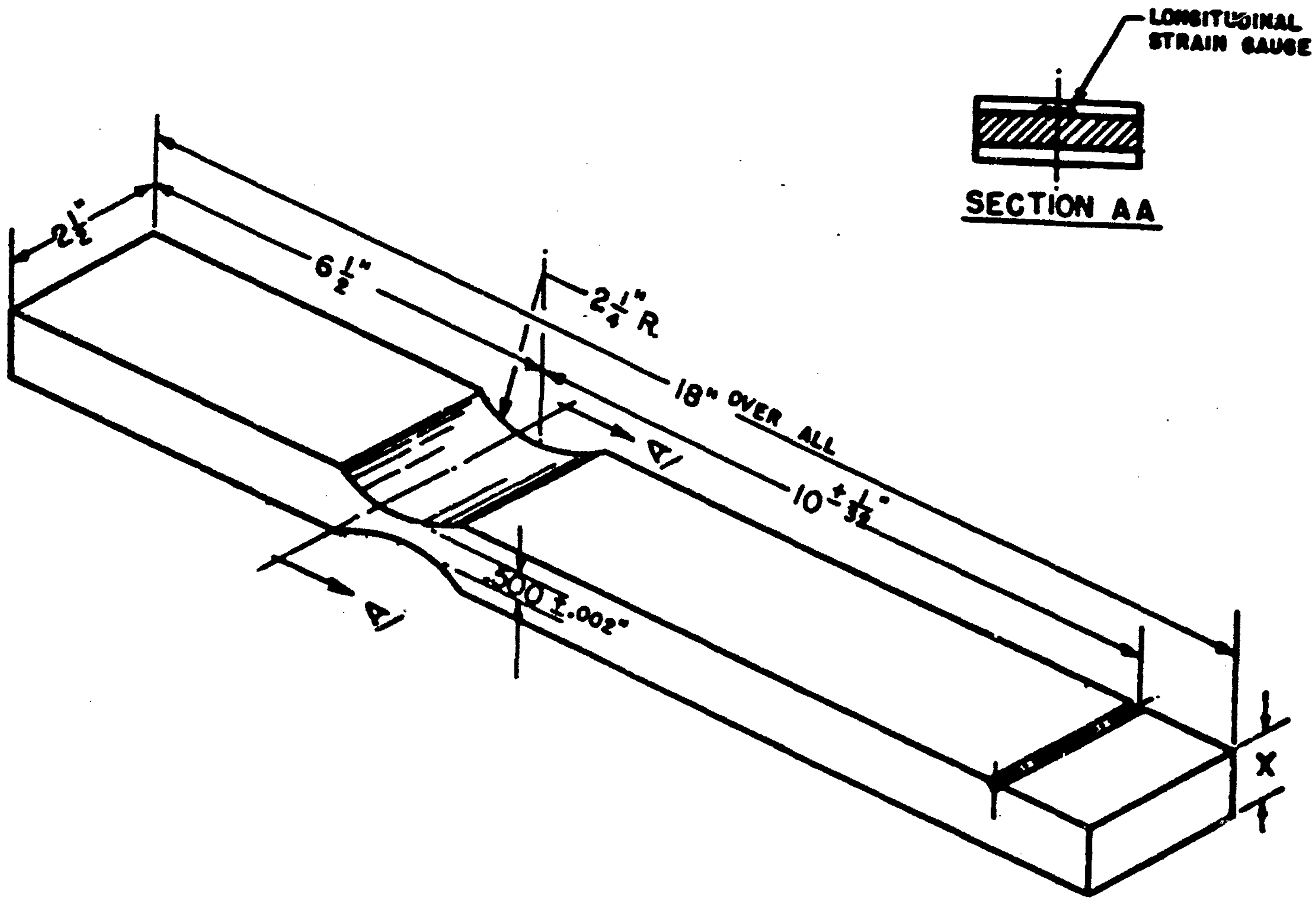

FIGURE 2 - LOW-CYCLE FATIGUE SPECIMEN

Title and Legend for Figures 3 Through 15

Title

Flexural Fatigue Curves

Legend

○ - Rotating Cantilever Fatigue Tests, Air

△ - Rotating Cantilever Fatigue Tests, Salt Water

● - Low-Cycle Fatigue Tests, Air

▲ - Low-Cycle Fatigue Tests, Salt Water

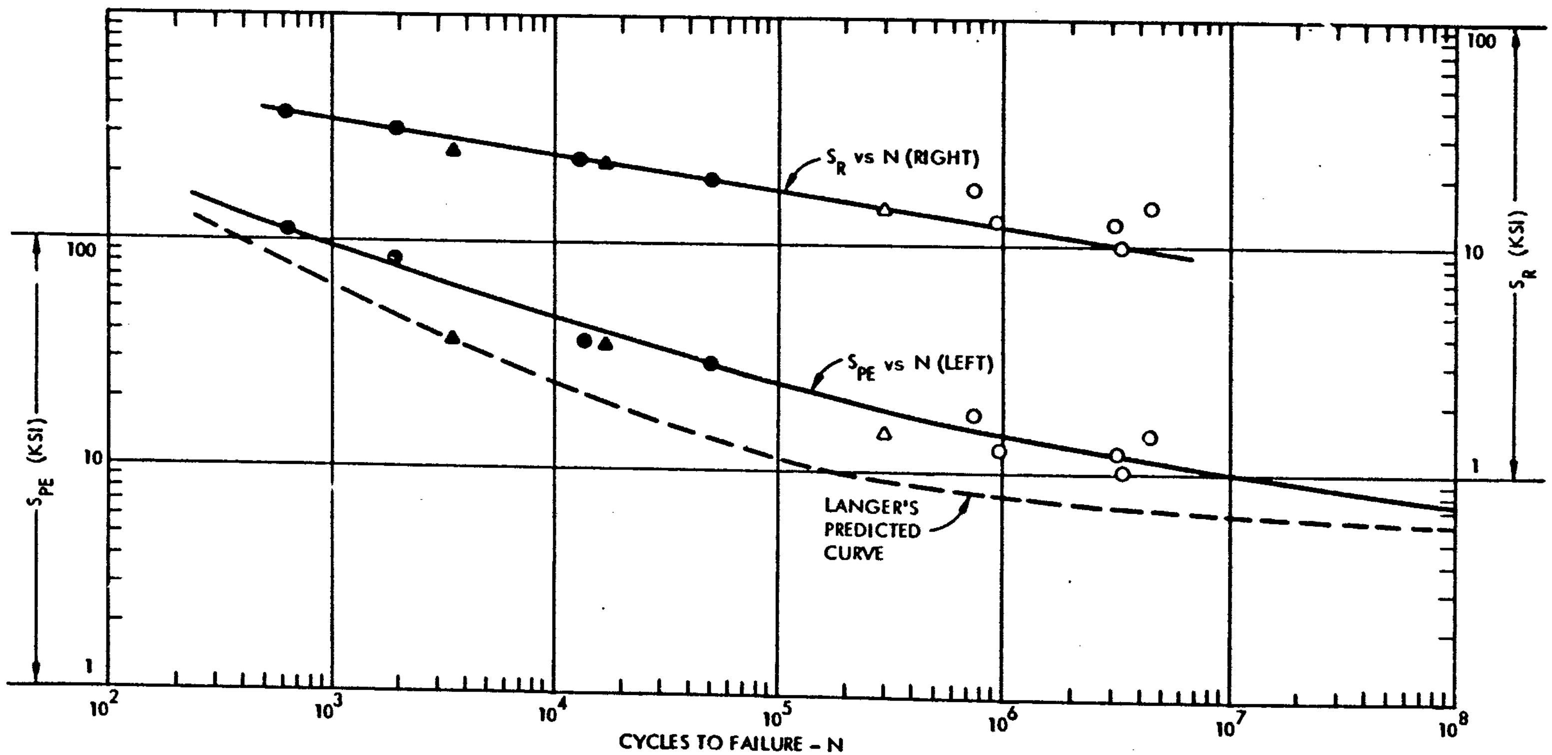

FIGURE 3 - GUN METAL (CAST) EQUATION: $S_{PE} = \dfrac{1.016 \times 10^6}{N^{0.35}} + 6{,}000$

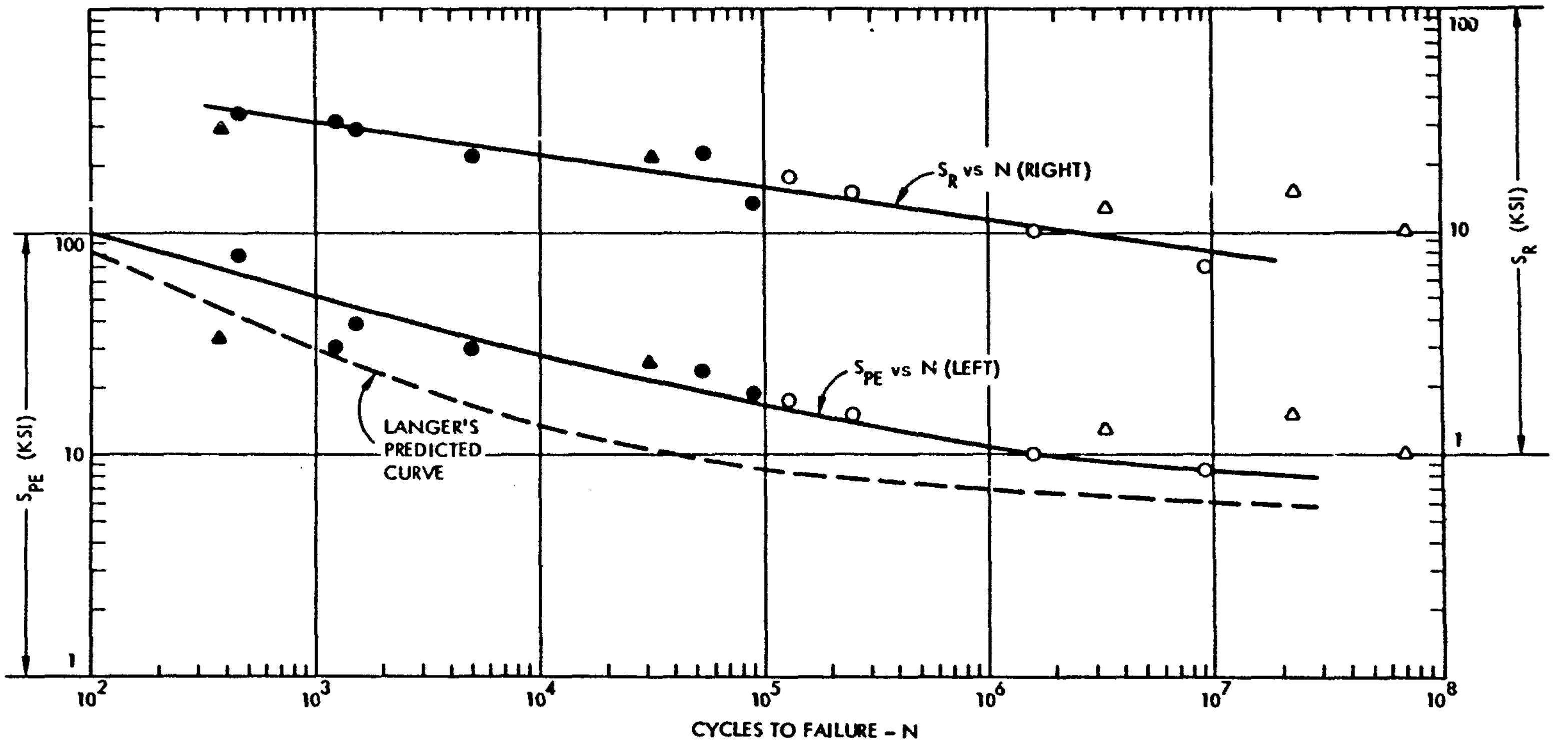

FIGURE 4 – VALVE BRONZE (CAST) EQUATION: $S_{PE} = \dfrac{4.03 \times 10^5}{N^{0.32}} + 6{,}000$

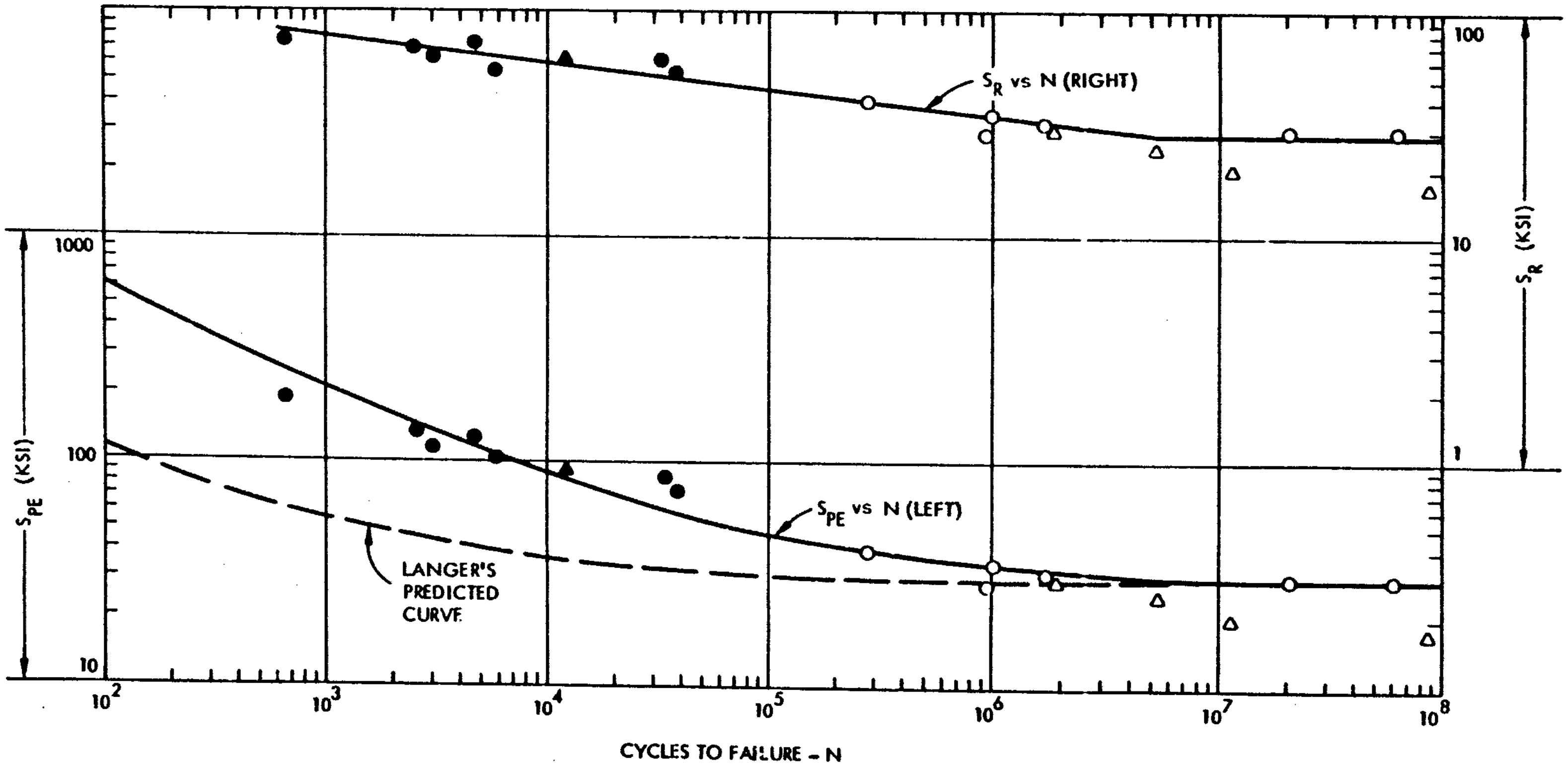

FIGURE 5 — Ni-Al BRONZE (CAST) EQUATION: $S_{PE} = \frac{5.57 \times 10^6}{N^{0.49}} + 29{,}000$

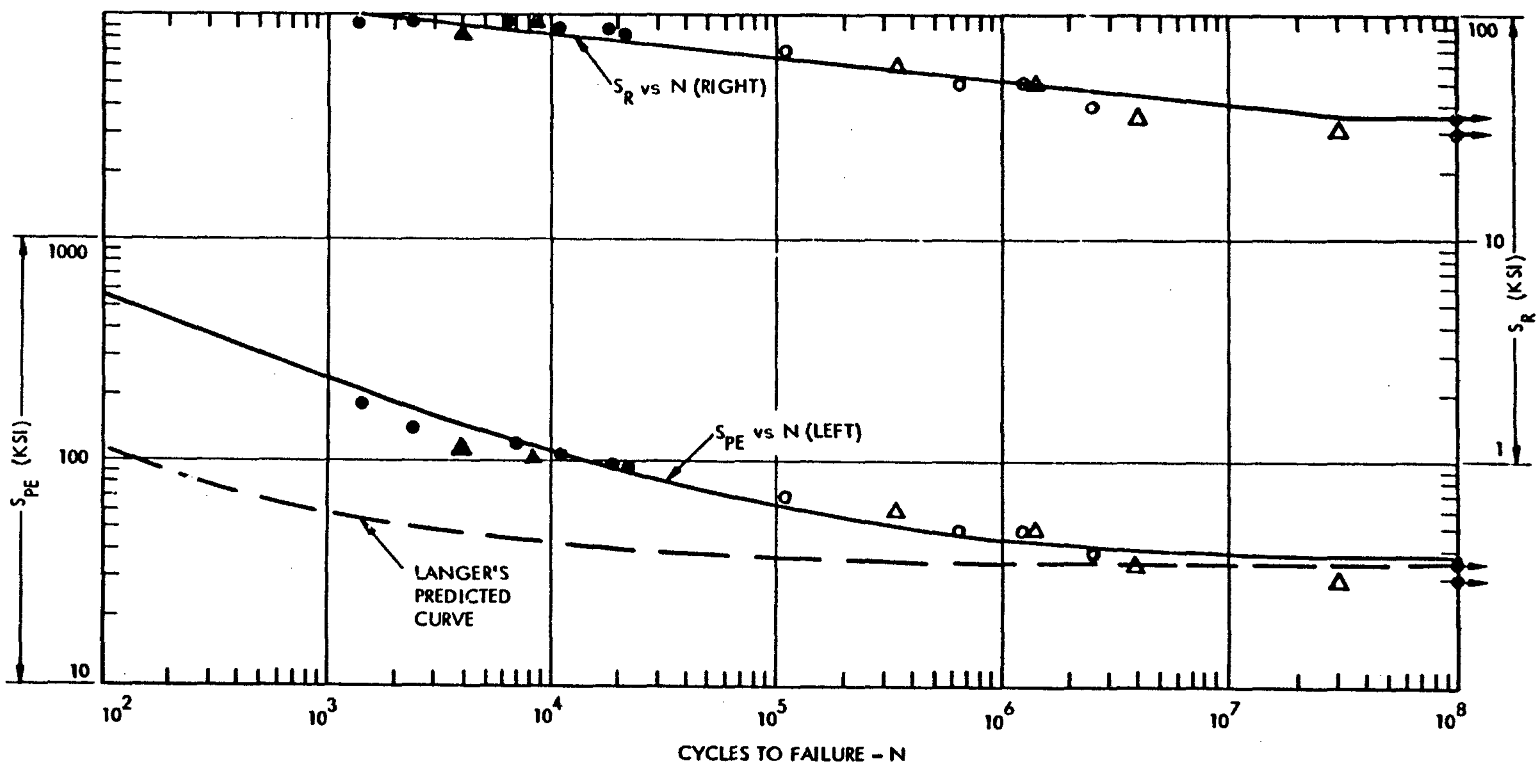

FIGURE 6 — Ni-Al BRONZE (FORGED) EQUATION: $S_{PE} = \frac{3.53 \times 10^6}{N^{0.42}} + 35,000$

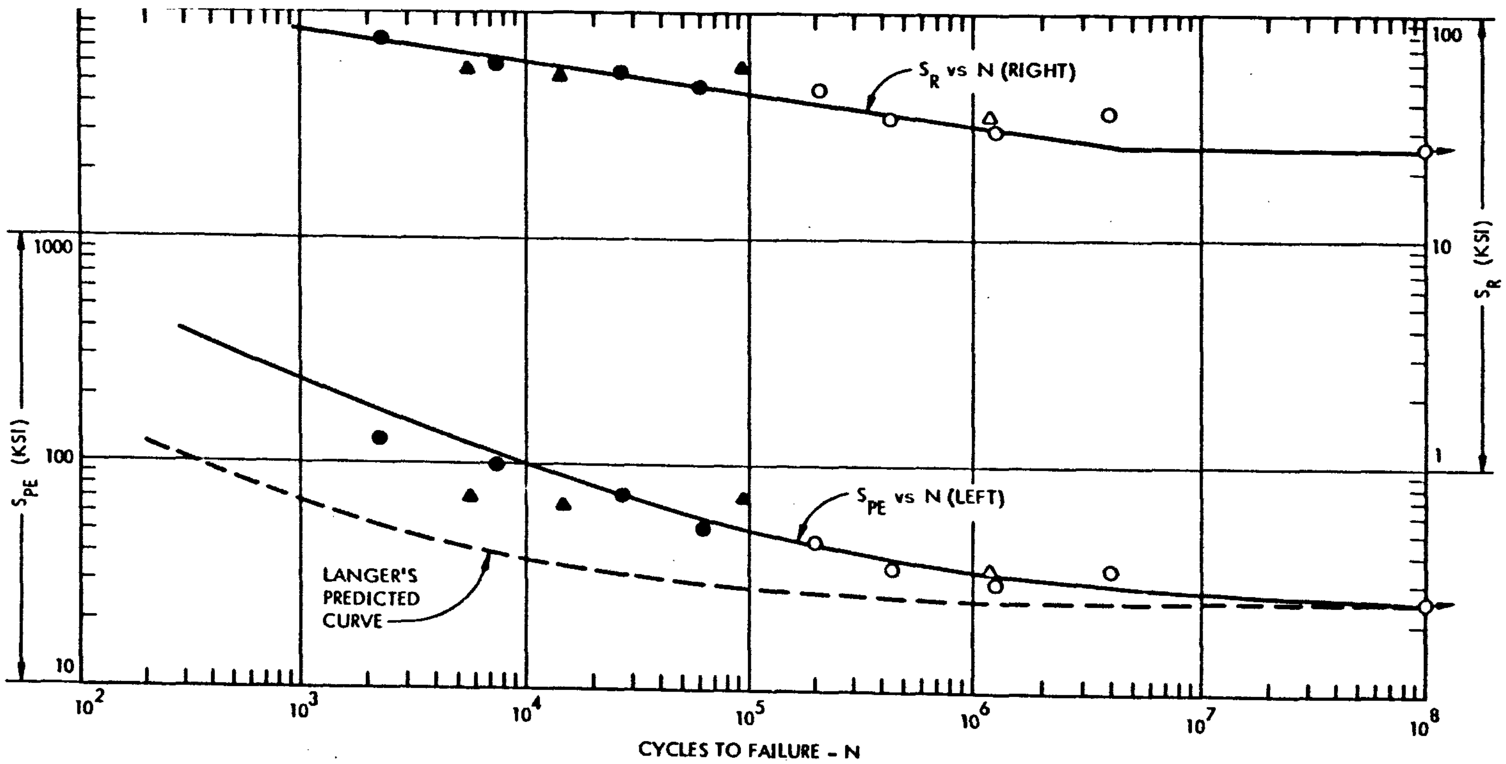

FIGURE 7 - SUPERSTON 40 (CAST) EQUATION: $S_{PE} = \frac{3.9 \times 10^6}{N^{0.44}} + 25,000$

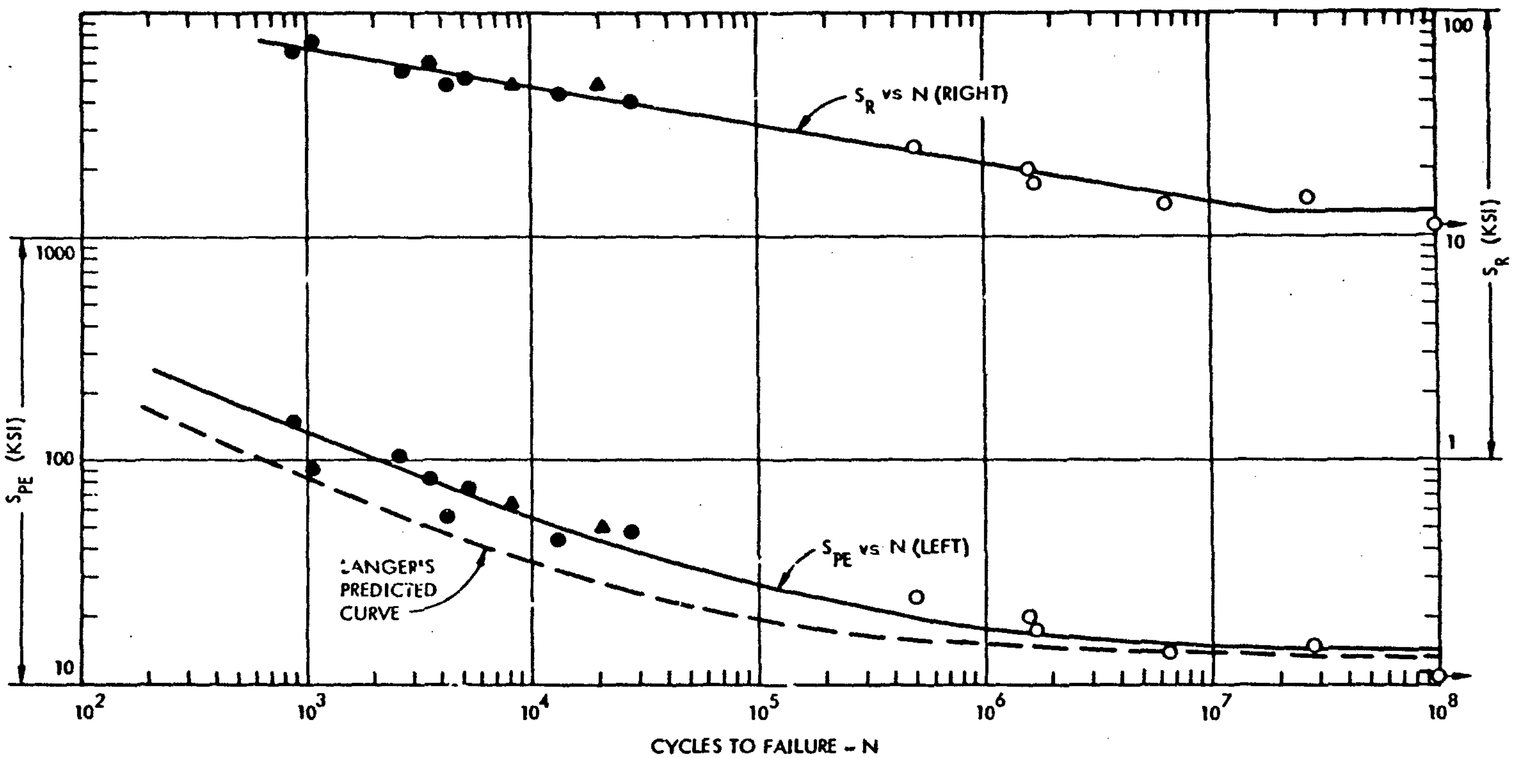

FIGURE 8 – 70–30 CUPRONICKEL (CAST) EQUATION: $S_{PE} = \frac{2.8 \times 10^6}{N^{0.45}} + 13,000$

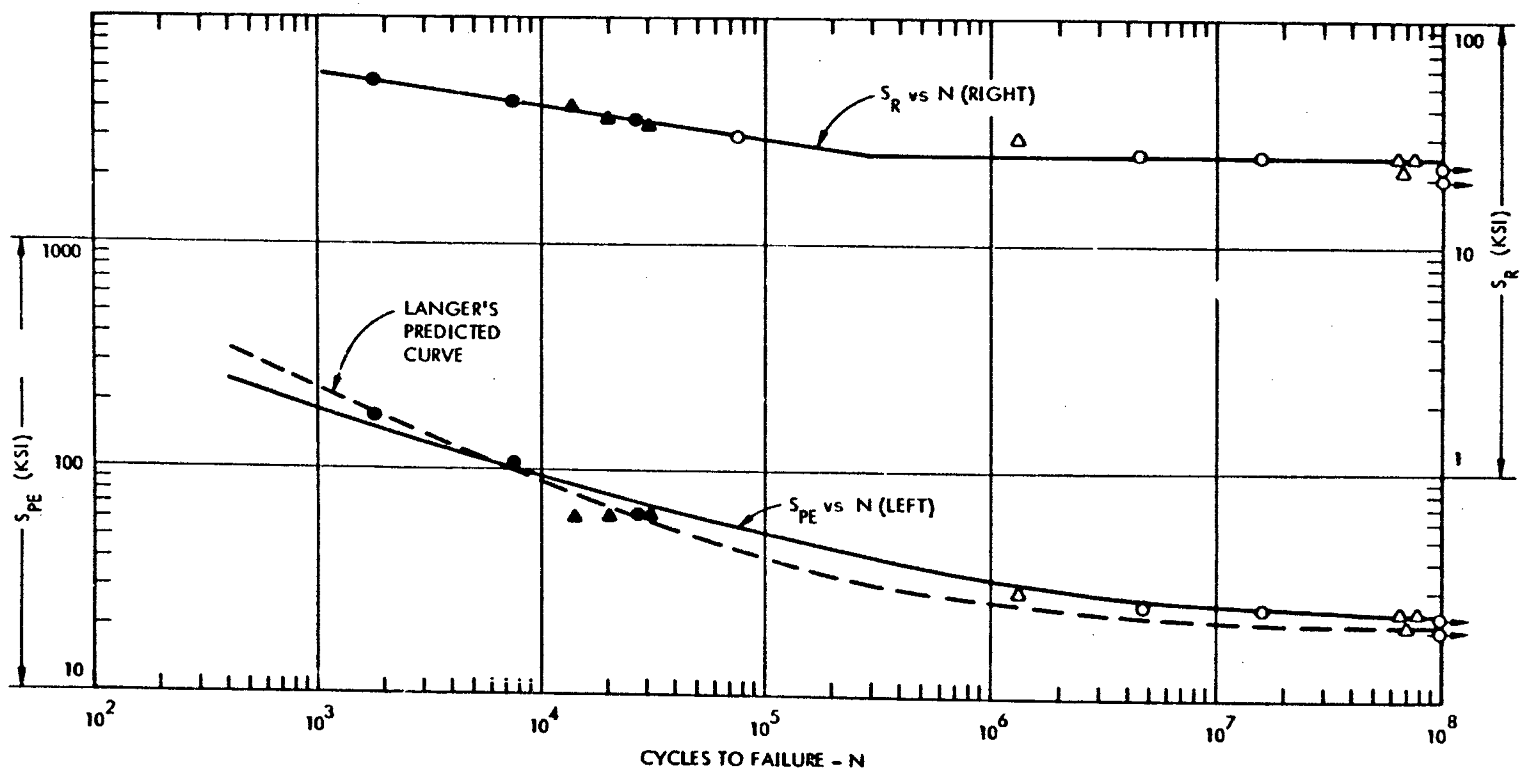

FIGURE 9 — 70-30 CUPRONICKEL (WROUGHT) EQUATION: $S_{PE} = \frac{1.90 \times 10^6}{N^{0.35}} + 20,000$

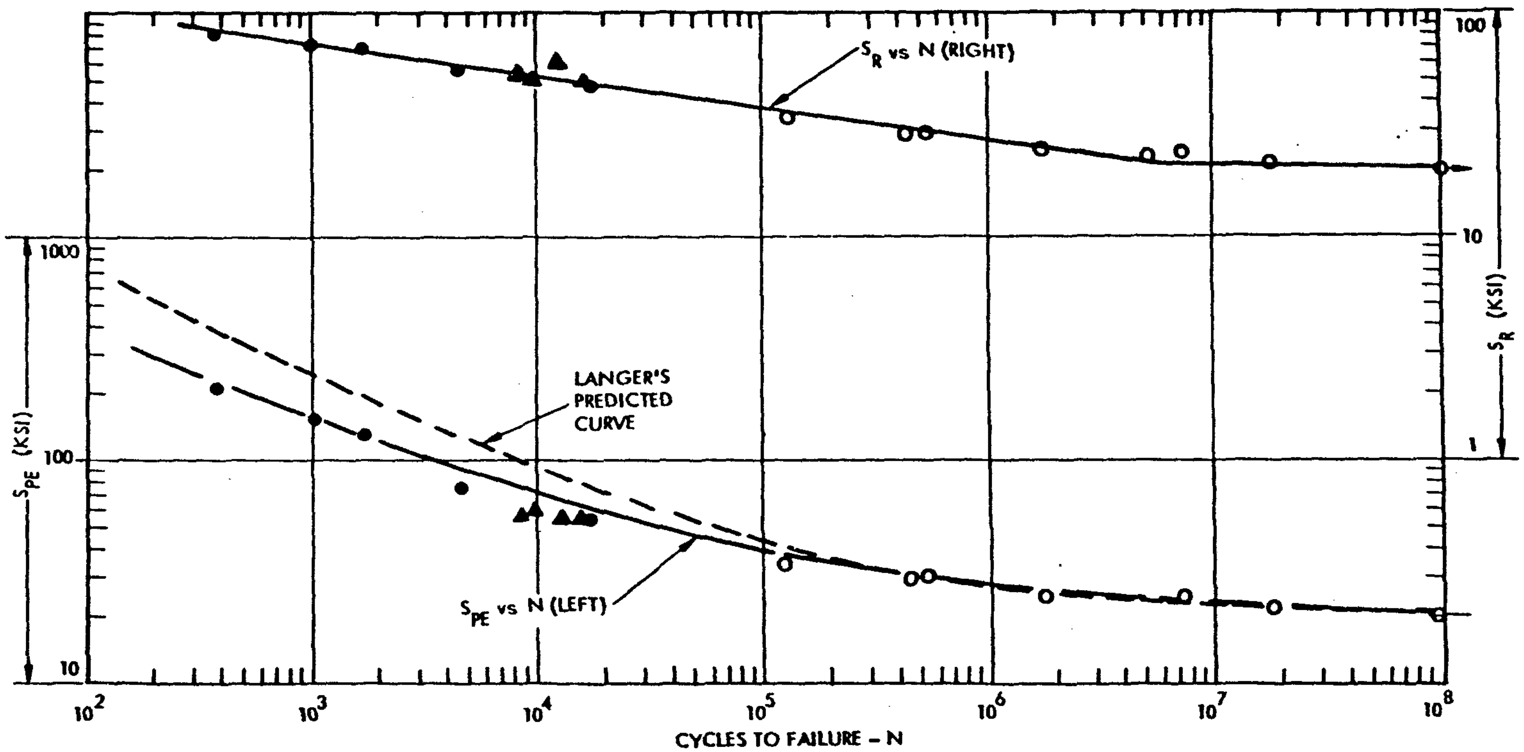

FIGURE 10 – 90-10 CUPRONICKEL (HARD) EQUATION: $S_{PE} = \frac{2.3 \times 10^6}{N^{0.42}} + 20,000$

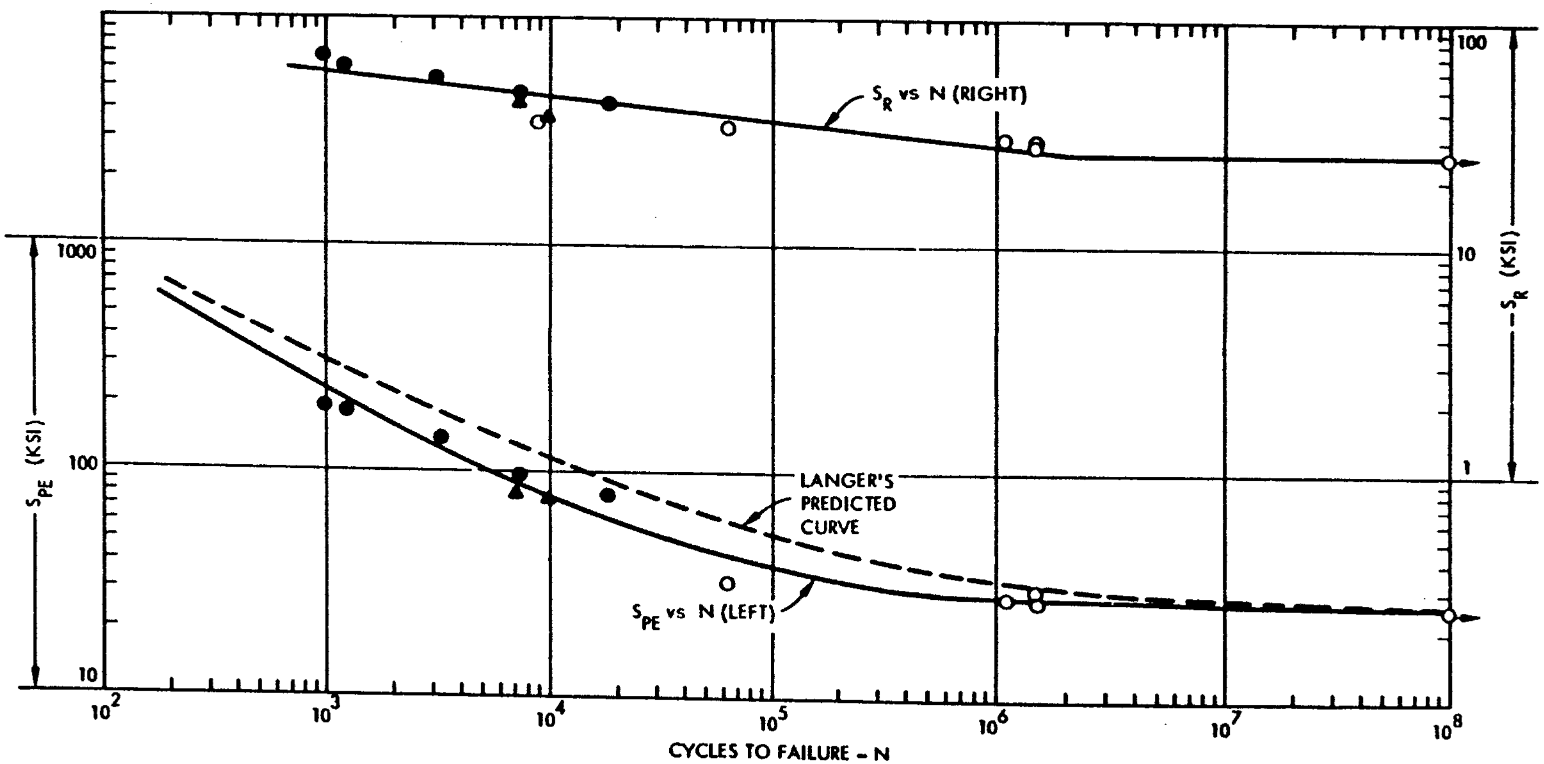

FIGURE 11 – CUFENLOY 40 (ANNEALED) EQUATION: $S_{PE} = \frac{1.1 \times 10^7}{N^{0.58}} + 25,000$

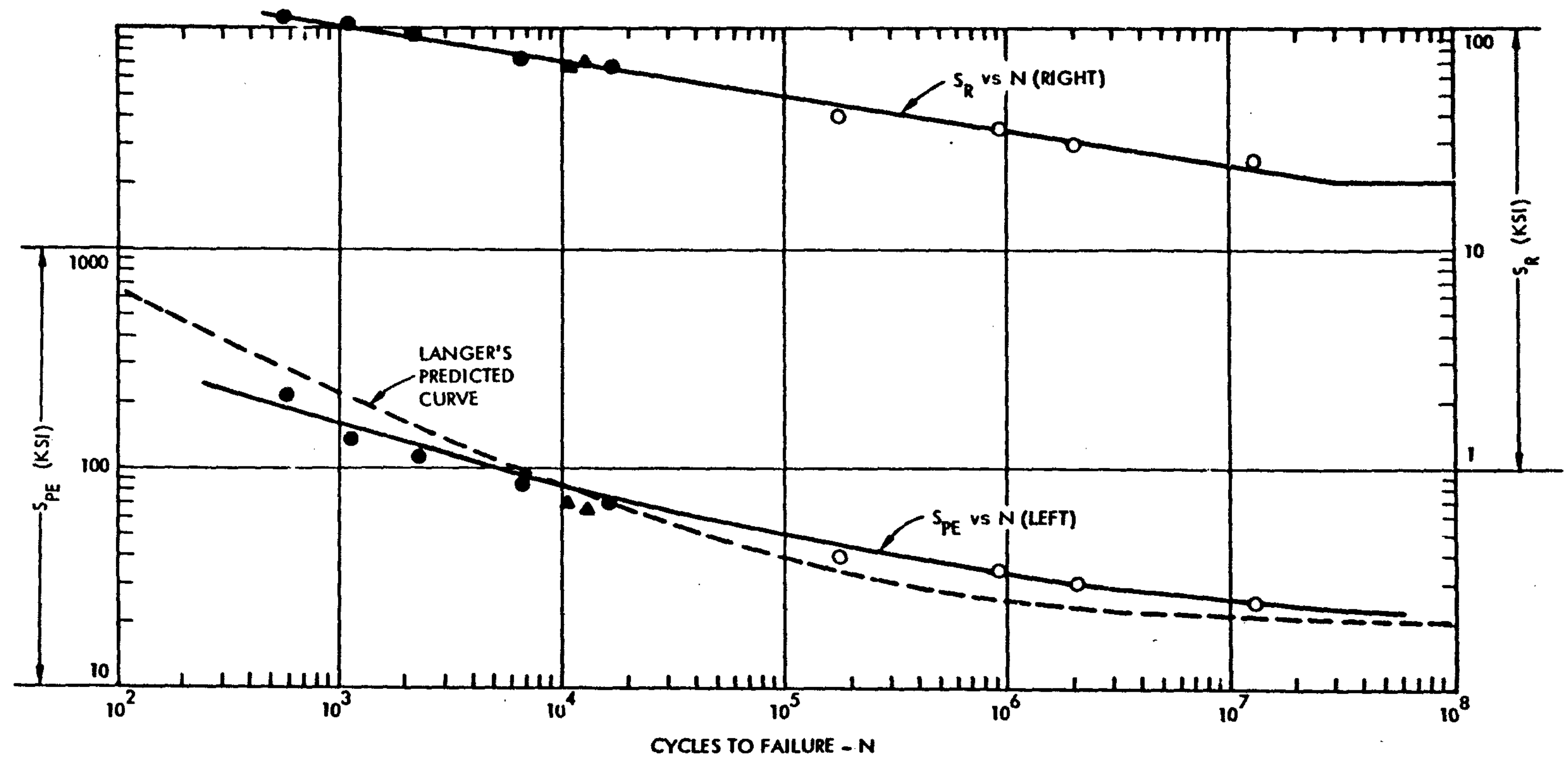

FIGURE 12- CUFENLOY 40 (DSR) EQUATION: $S_{PE} = \frac{1.4 \times 10^6}{N^{0.34}} + 20{,}000$

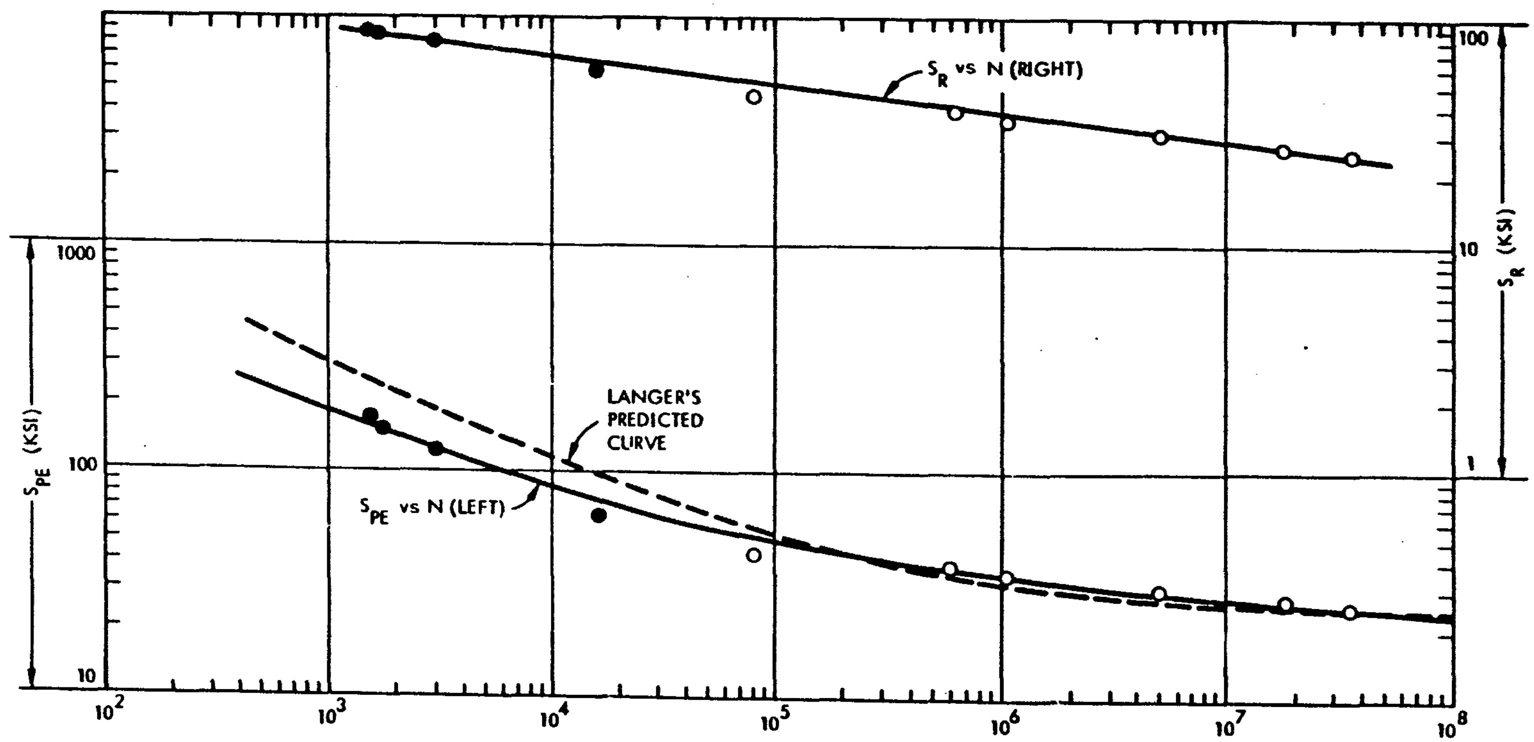

FIGURE 13 – CUPRONICKEL 707 (WROUGHT) EQUATION: $S_{PE} = \frac{2.4 \times 10^6}{N^{0.39}} + 23,000$

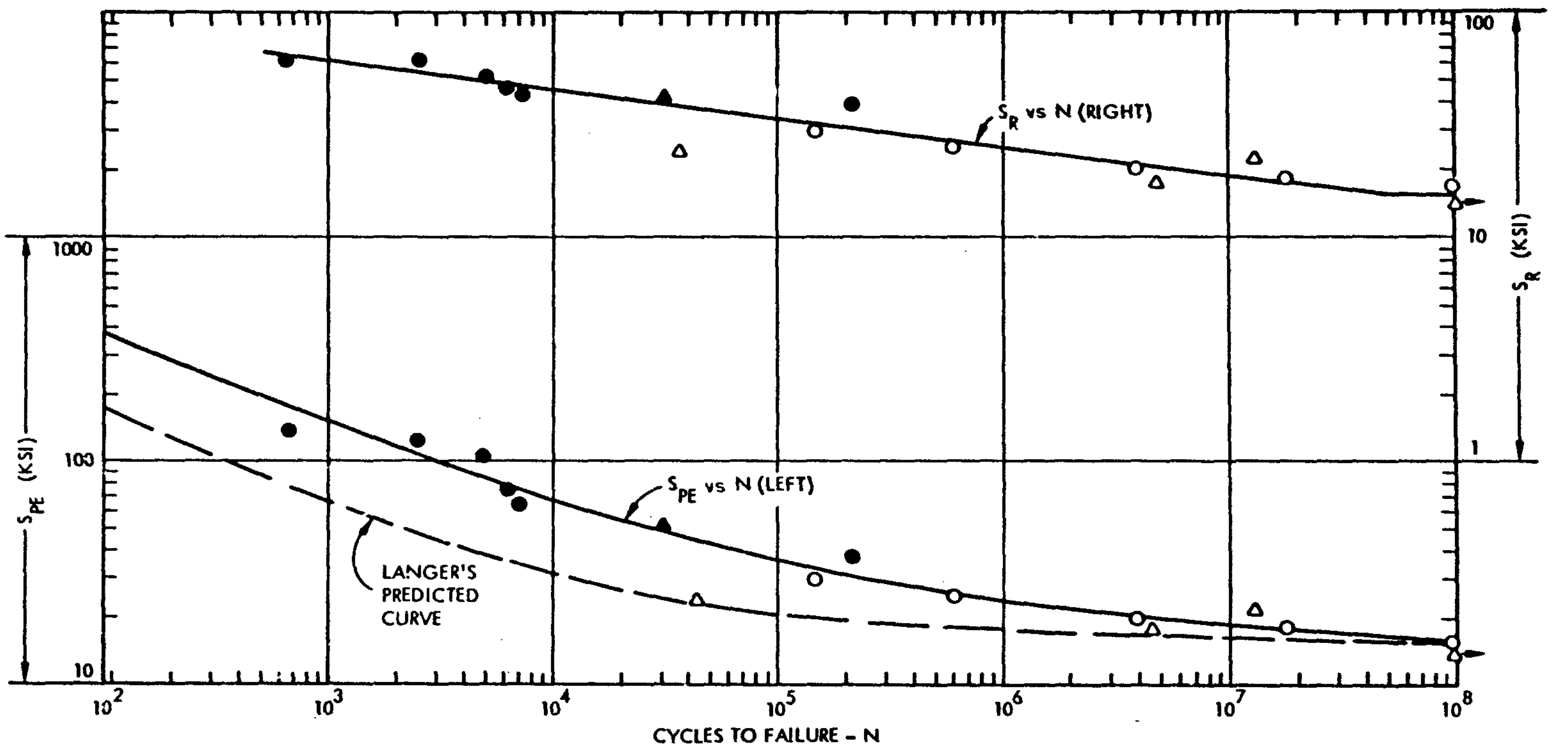

FIGURE 14–MONEL "E" (CAST) EQUATION: $S_{PE} = \frac{2.51 \times 10^6}{N^{0.42}} + 16,000$

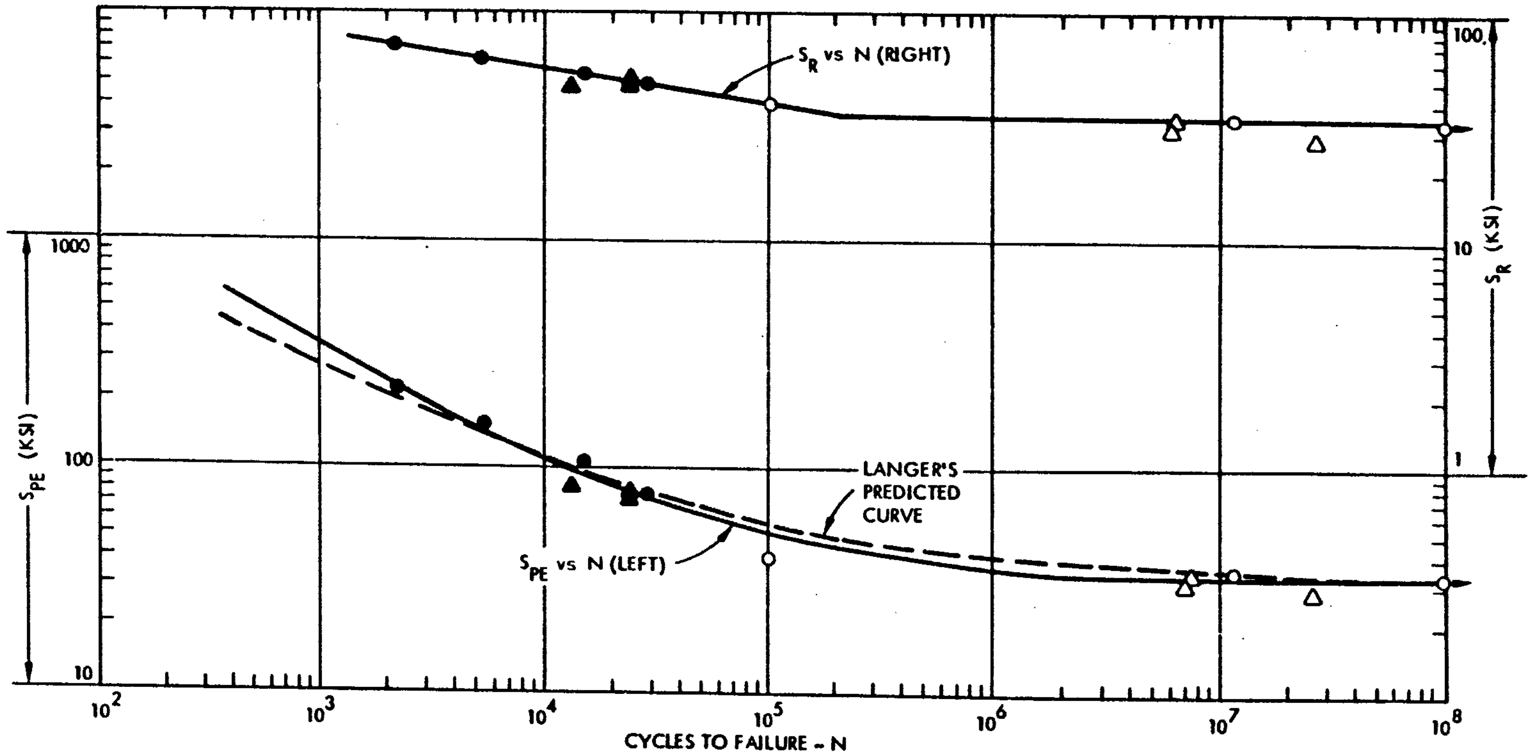

FIGURE 15-MONEL (WROUGHT) EQUATION: $S_{PE} = \frac{2.1 \times 10^7}{N^{0.61}} + 33{,}000$

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